Laser-based RF Precision Oscillators

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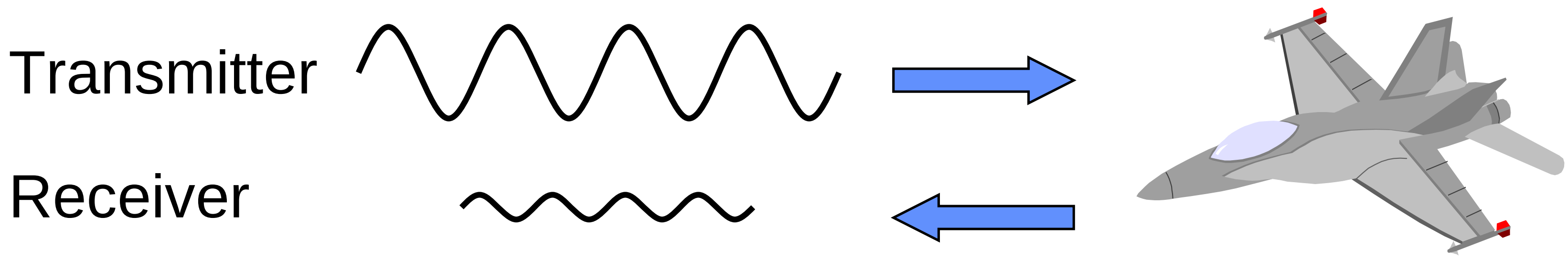
Outline

- Background – Doppler radar
- CO_2 laser RF source
- Nd:YAG laser RF source
- Summary of proposed work

Doppler Shift

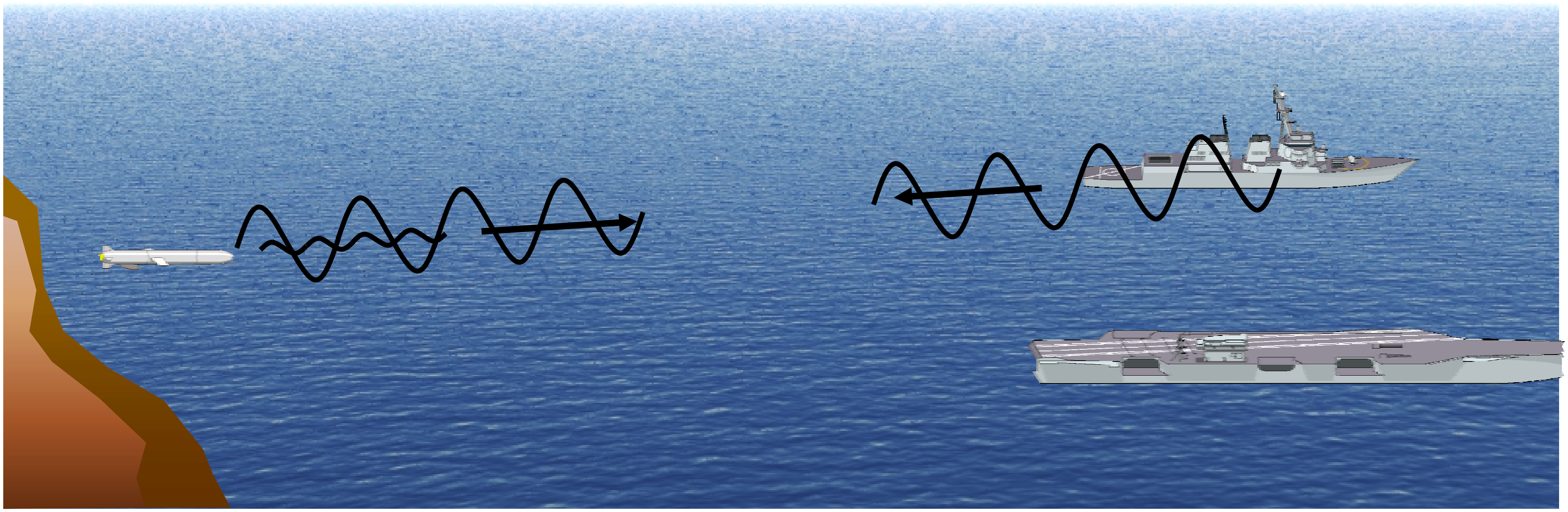


- **Target moving towards you shifts return up in frequency, away => down**
- **Doppler shift is proportional to frequency = f * 2v/c**
- **Doppler shift often separates target from background clutter**

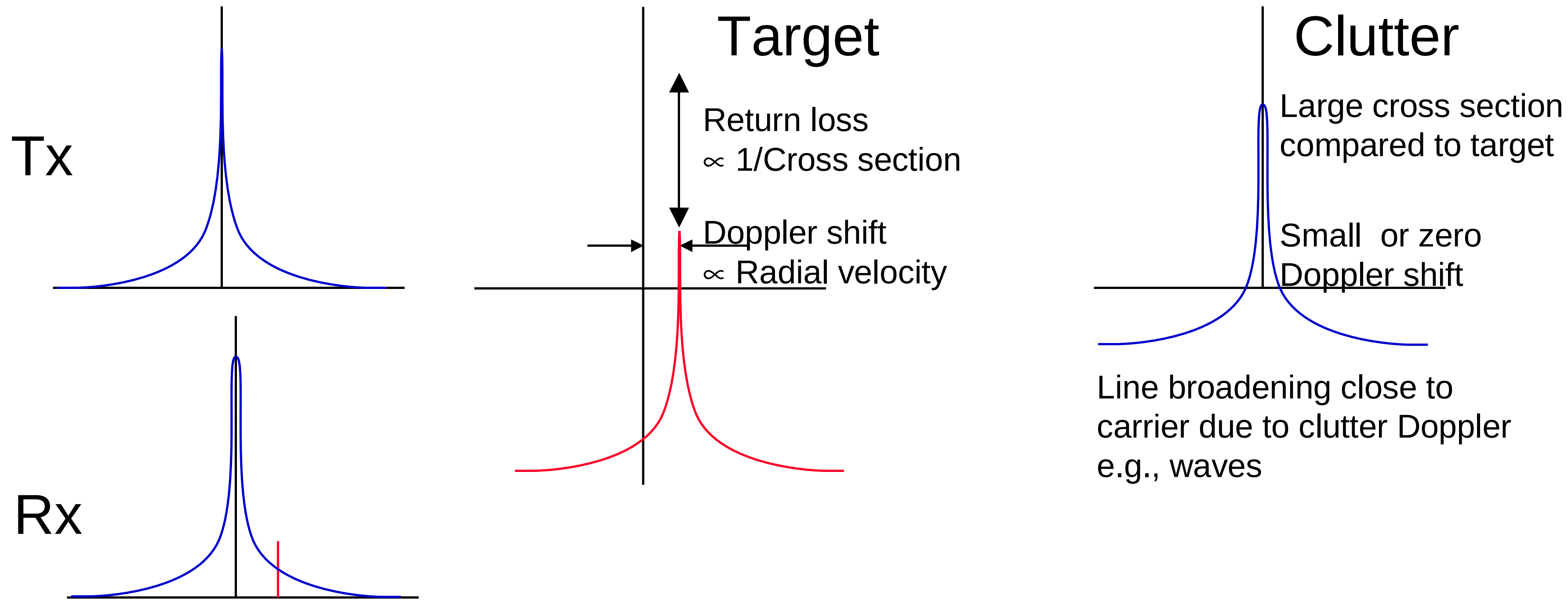
	S-Band (3 GHz)	X-Band (10 GHz)
Crawl (1/4 m/s)	5 Hz	17 Hz
Walk (1 m/s)	20 Hz	67 Hz
Drive (10 m/s)	200 Hz	667 Hz
Fly (100 m/s)	2000 Hz	6.67 kHz
Mach 1 (340 m/s)	6.8 kHz	22.7 kHz
LEO (7000 m/s)	140 kHz	467 kHz

Targets Hide in Clutter

- **Clutter (environmental returns) gives *huge* signal compared to target, can be > 10^6 larger for some targets**
- **Target return is slightly Doppler shifted in frequency**
- **Clutter returns transmit signal and transmit noise**
- **Transmit noise in clutter return can hide target**
- **Better oscillator helps see small targets hiding in clutter**

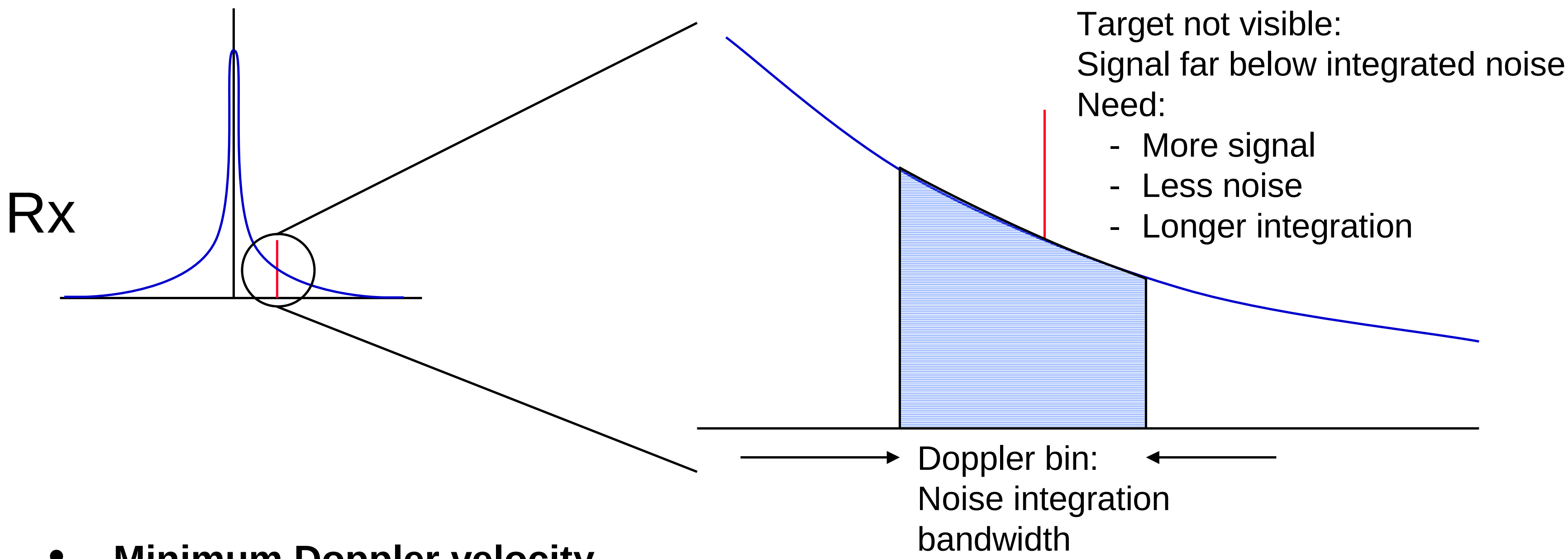


Oscillator noise in a Doppler radar system can obscure the target



- **Oscillator noise is transmitted, blurring the return, and mixed into the return in the receiver.**
- **Noise raises the noise floor, particularly for small frequency shifts (small Doppler velocity)**
- **This limits the ability to see small targets with small velocity against clutter**

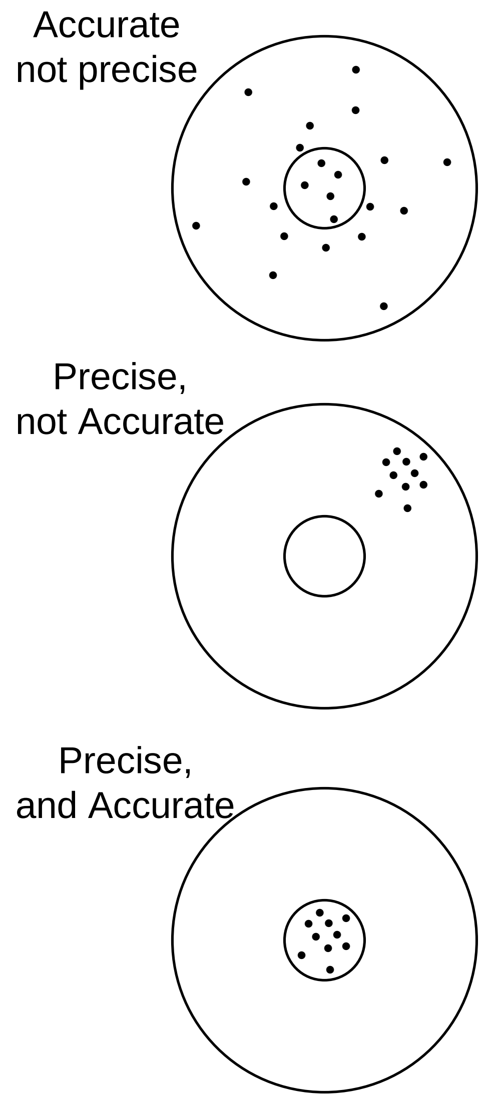
Doppler Bin-width Sets Detection Limit



- **Minimum Doppler velocity**
  - **Integration time**
  - **Clutter doppler**
  - **Phase noise**
- **Doppler bin width set to ~10% of Doppler frequency**
- **Sets clutter & phase noise bandwidth**
- **Clutter Improvement Factors (CIF) of 60 to 110 dB needed**

State of the Art

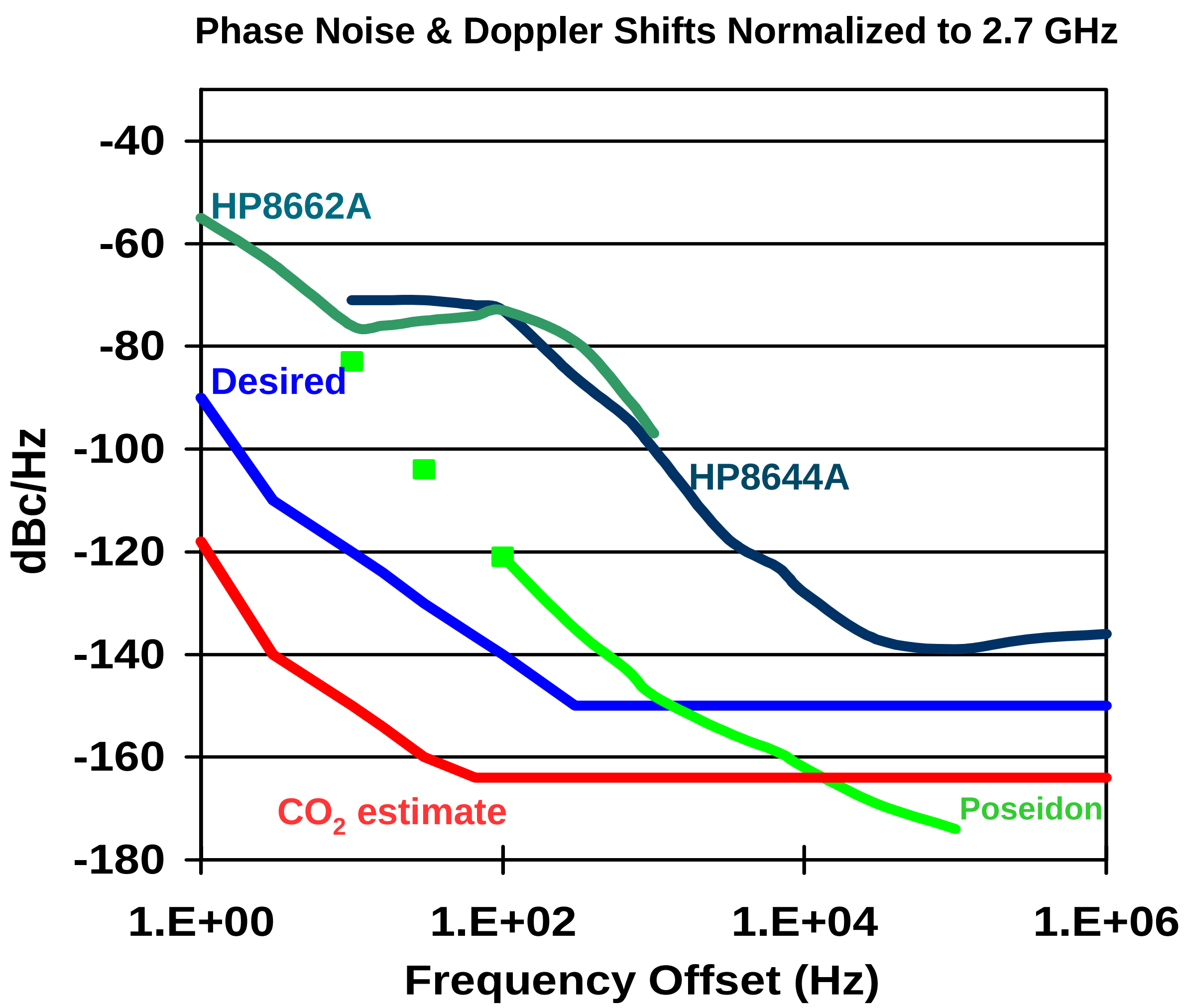
- **For times < 1 sec, Quartz is standard to beat**
- **Atomic clocks use “physics package” for long term *accuracy***
  - **Terrible SNR**
  - **Shot noise limited with small number of photons**
  - **Accurate by virtue of fundamental physics**
  - **Long (>1000 sec) integration times**
- **“Flywheel” used for short term *precision***
  - **Quartz**
  - **Ultra-stable cavity, CO_2 or Nd:YAG lasers**
    - **Path to long-term accuracy – locking laser to an atomic reference**



Desired Phase Noise Spectrum

Caveats

- All sources normalized to 2.7 GHz
  - 6 dB/octave ideal multiplier or divider
- “Desired” assumes
  - Ideal RF components
  - 12 bit digitizer limits SNR
- CO_2 phase noise estimate
  - Allen variance translation
  - 2 - laser tests
  - 10 mW shot noise into ideal detector



Schawlow-Townes linewidth gives the quantum noise limit for a laser cavity

$$\Delta\nu = \left(\frac{ahc^2}{4\pi}\right)\frac{T^2\nu}{L^2 P_{out}}$$

T=round-trip cavity loss
ν=optical frequency
L=cavity length
P_{out}=output optical power
h=Planck's constant
a=inversion parameter (≈1)
c=light speed

CO_2

T≈3%,
L≈0.5m, $\rightarrow$ $\frac{\Delta\nu}{\nu} \approx$ **$2\text{x}10^{-20}$**
P≈1W,

$\Delta\nu \approx$ **$5\text{x}10^{-7}$ Hz**

Nd:YAG

T≈2%,
L≈0.07m, $\rightarrow$ $\frac{\Delta\nu}{\nu} \approx$ **$2\text{x}10^{-17}$**
P≈0.02W,

$\Delta\nu \approx$ **$5\text{x}10^{-3}$ Hz**

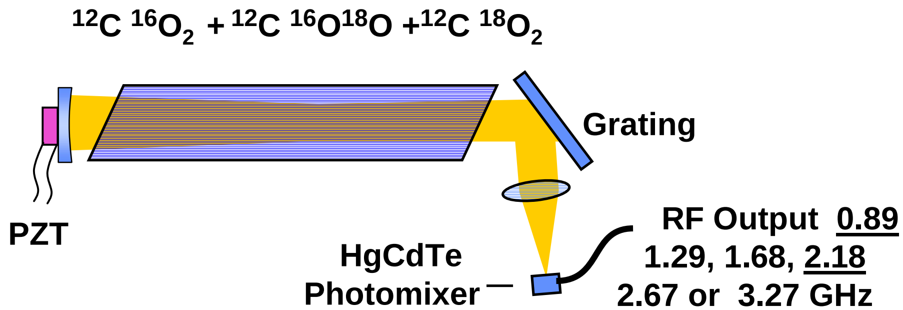
Using a two-frequency laser as a quiet RF oscillator

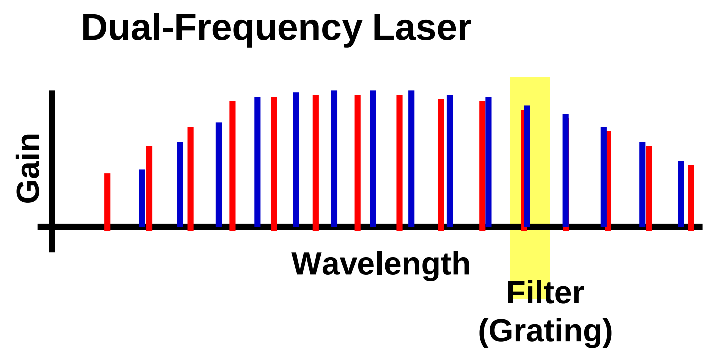
- **A laser's optical frequency can be much quieter than state-of-the-art crystal oscillators.**
- **Optical frequencies (~100THz) cannot be detected by photodetectors, but a photodetector can see the beat frequency between two closely spaced optical frequencies.**
- **The optical frequency noise depends on laser cavity length instability which will map onto the RF beat frequency if the two frequencies are spatially overlapped in the same cavity:**

$$\frac{\Delta L}{L} = \frac{\Delta \nu_{opt}}{\nu_{opt}} \left(= \frac{\Delta f_{RF}}{f_{RF}} \right)$$

- **Single cavity eliminates many common-path errors**

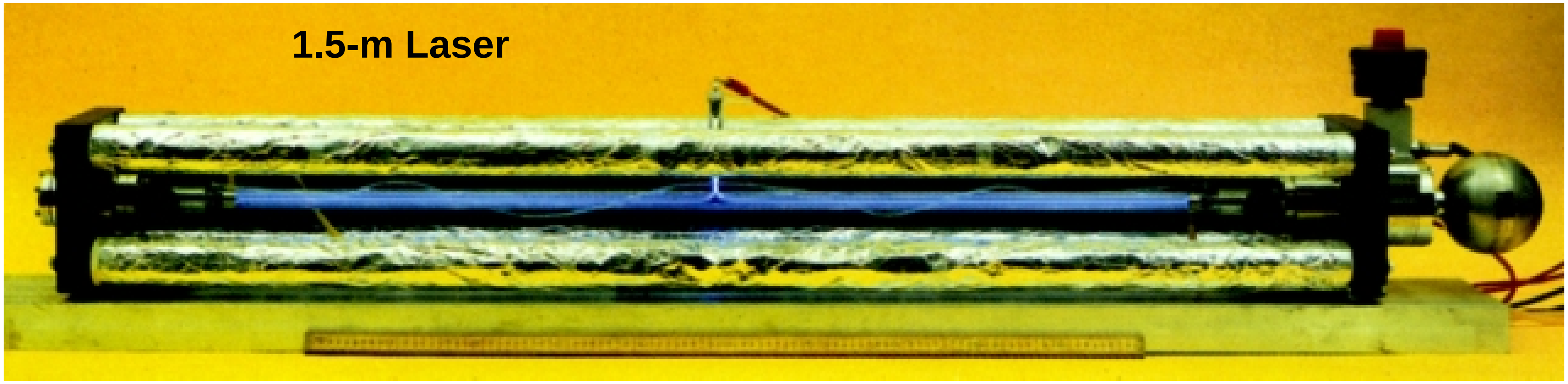
CO_2 -Laser-Based RF Frequency Reference





- RF beat note (f_{RF}) from dual-frequency, single-cavity laser
- Common optical cavity minimizes RF noise, drift, thermal effects, acoustic effects,etc.
- In 1979, $\Delta f_{RF}/f_{RF}$ was found to be less than that of hp 8672A synthesizer for times < 200 µs

Characteristics of Freed CO_2 Lasers



Features

Super invar spacer rods with thermal, vibration, acoustical & magnetic shielding

Black Diabase granite end plates, Stabilized DC plasma discharge

Achieved $\Delta\nu/\nu < 2 \times 10^{-13}$

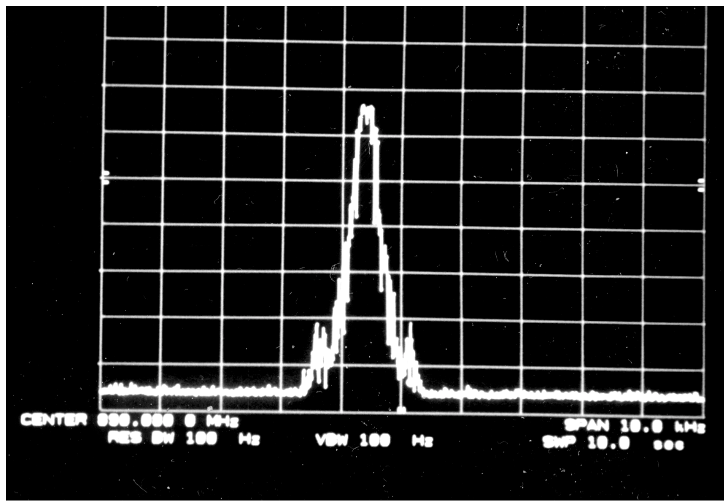
Laser	Gain Length (m)	Comments
1.5-m Grating Output Coupled	1.23	Long gain region, mixed isotopes ok
0.5-m Two-Mirror	0.23	High-reflectivity mirrors needed for mixed isotopes

890 MHz Beat from Two-Frequency Mixed-Isotope CO_2 Laser

$^{16}O^{12}C^{16}O$ I P(12) and $^{16}O^{12}C^{18}O$ I $\overline{\mathrm{P}}$(19) Lines

100 Hz Instrument Resolution

10 dB/div



1 kHz/div

~0.3 mW of CO_2 Power on Photomixer
-28 dBm from HgCdTe Photomixer
+2 dBm with 30-dB amplifier

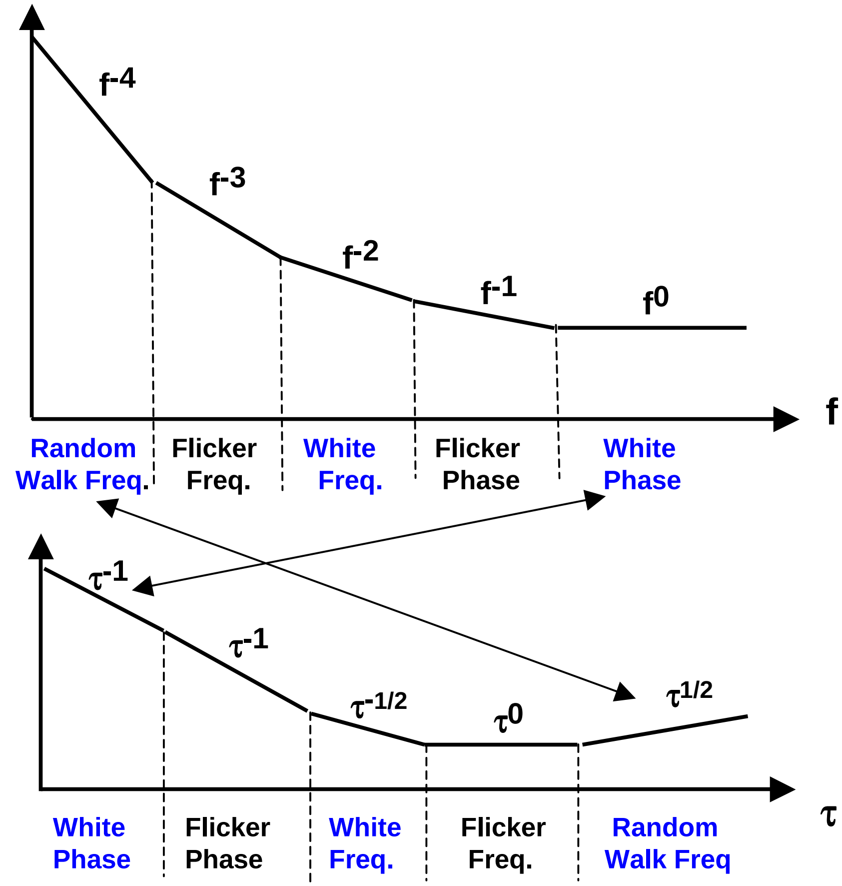
Phase Noise (f) and Allan Variance (τ)

Frequency Domain
Phase Noise Spectrum

$\mathcal{L}(f)$

Time Domain
Root-Allan Variance Plot

$\sigma_y(\tau)$

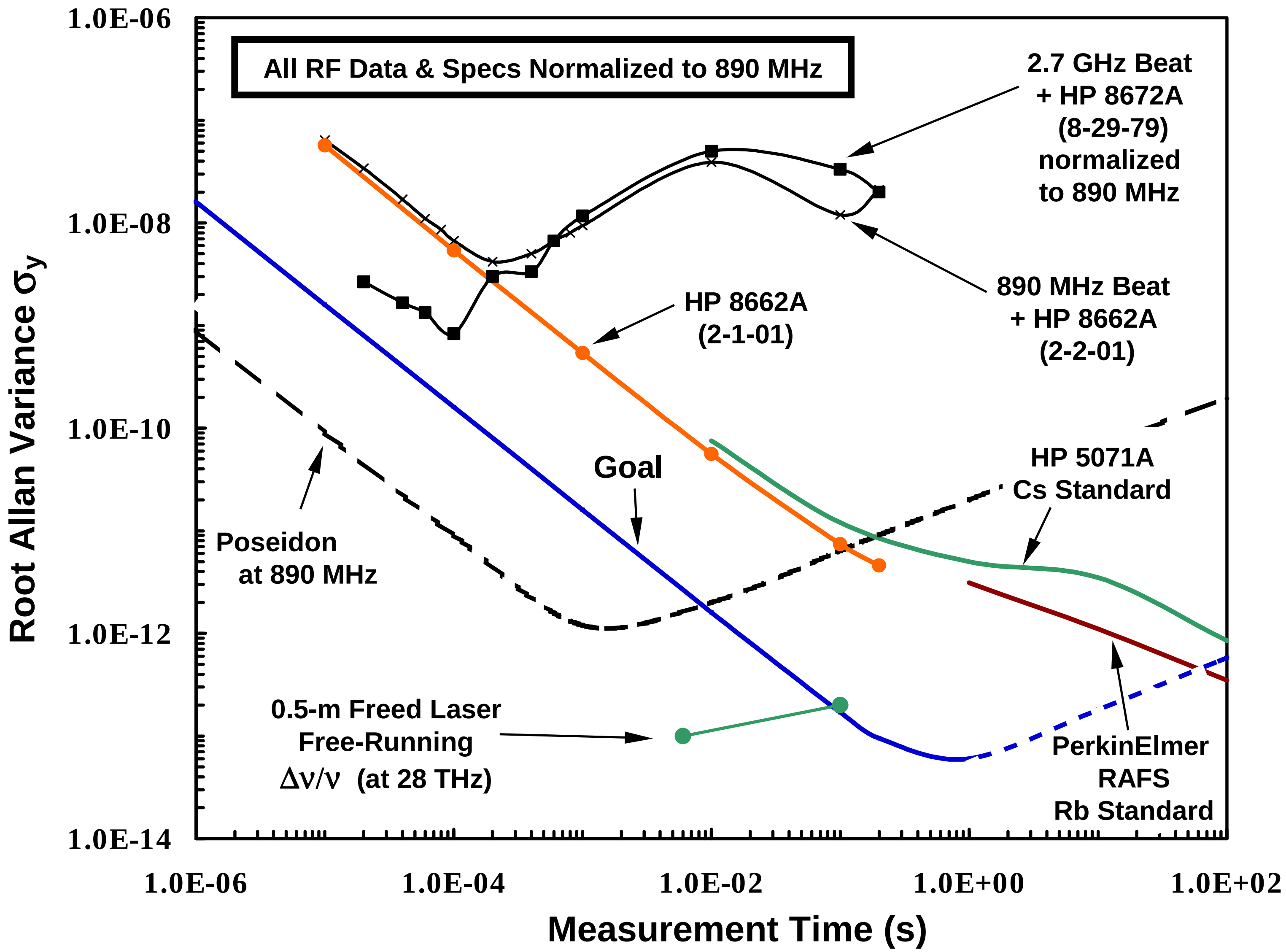


$$\sigma_y(\tau) \cong \frac{1}{f_0}\sqrt{\frac{\sum_{k=1}^{N-1}\left(f_{k+1}-f_k\right)^2}{2\,(N-1)}}$$

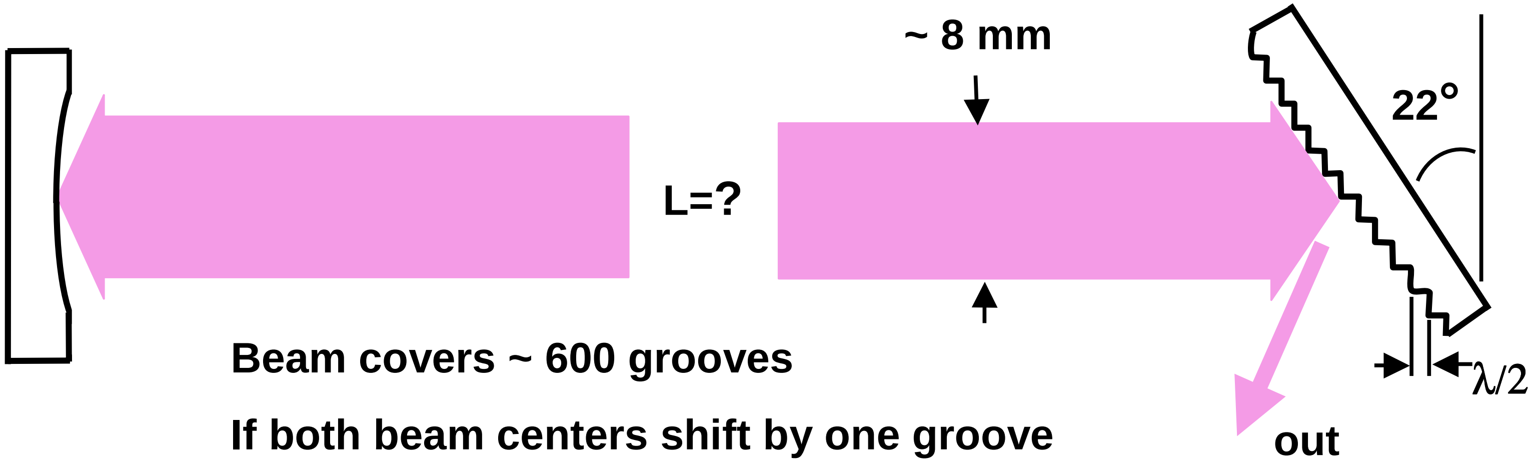
Closer to Carrier →

← Short-Term Stability

CO_2 Laser Root Allan Variance Data



No Precise Cavity Length in Grating Laser

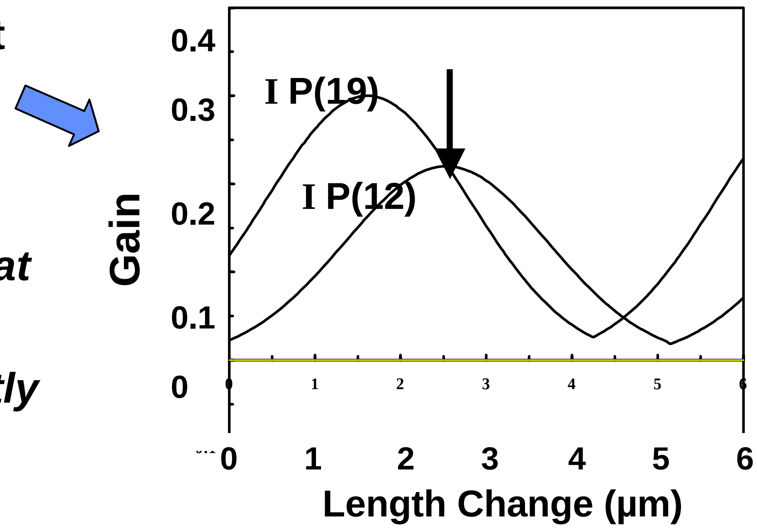


Beam covers ~ 600 grooves

If both beam centers shift by one groove

L shifts by $\lambda/2$ and f_{RF} shifts by ~ 3 kHz

Gain slope at P(19) operating point pulling towards shorter cavity

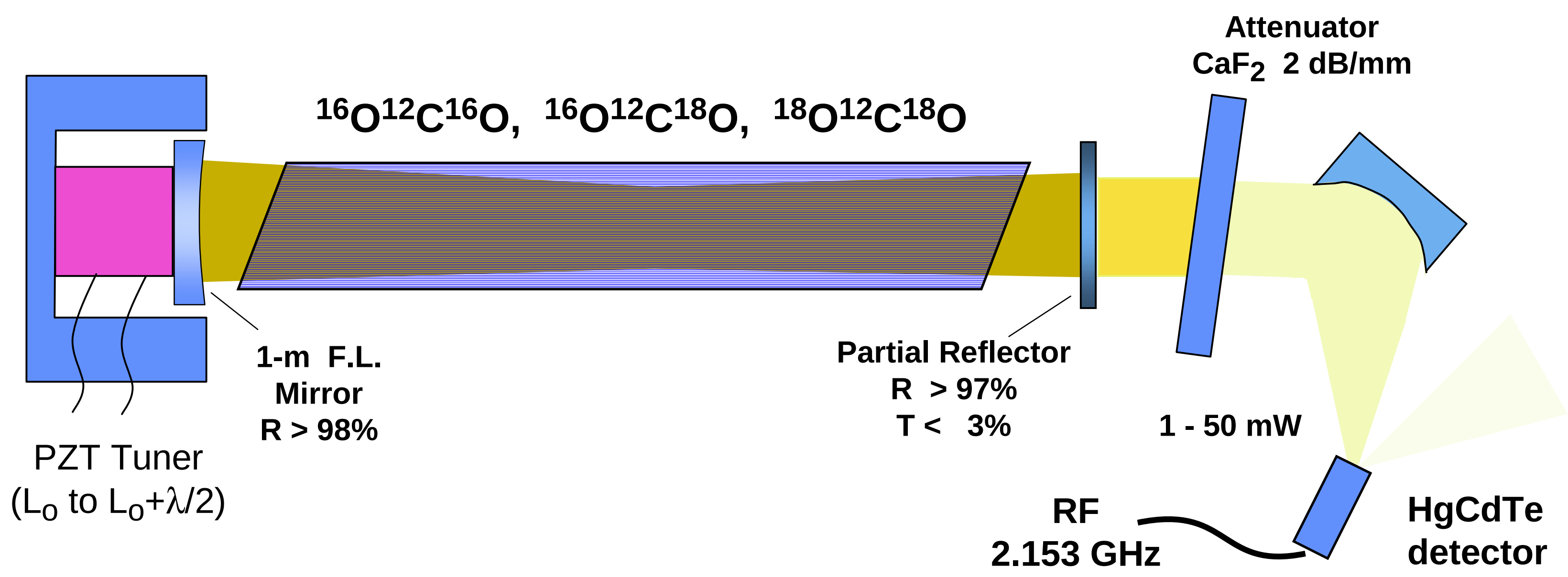


Anomalously large variations in 890-MHz beat frequency are a result of

626 I P(12) and 628 I P(19) operating at slightly different cavity lengths (1 nm ~ 19 kHz)

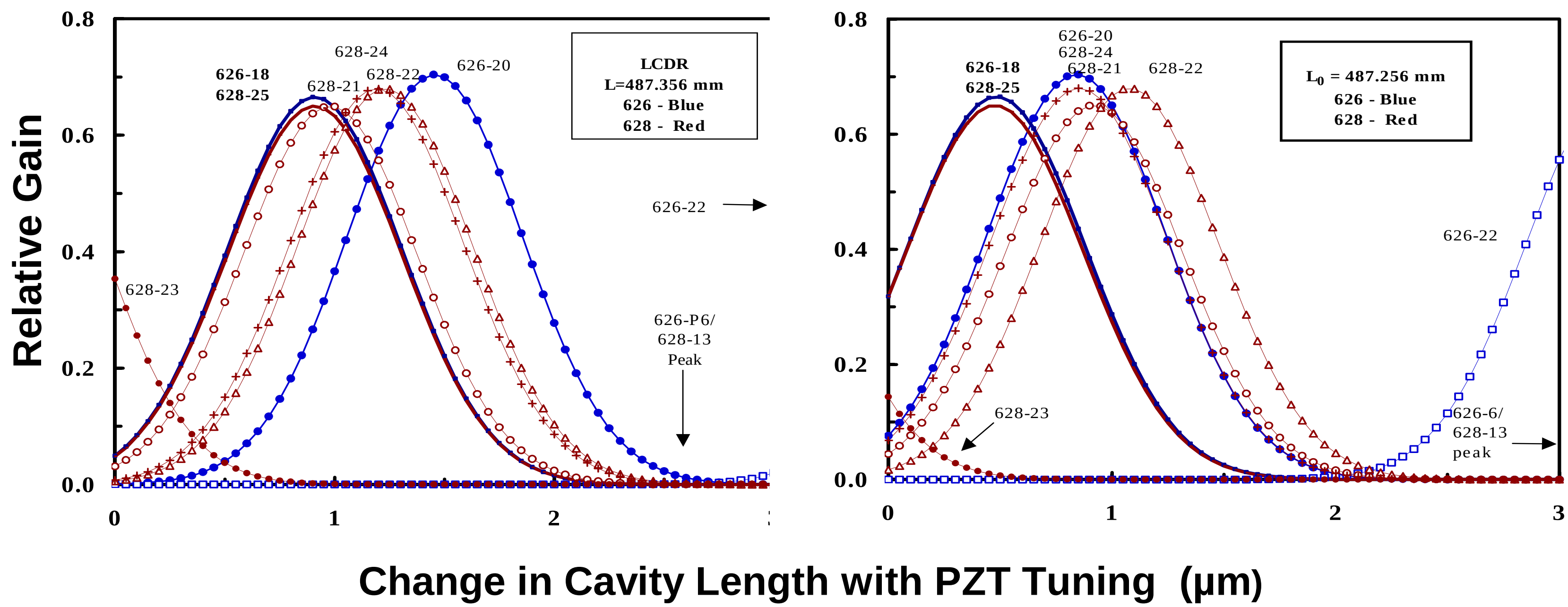
Dual-Frequency, Two-Mirror Single-Cavity Laser

- Dual-frequency, single-cavity laser minimizes RF phase noise
- 0.5-m two-mirror Freed lasers have shown 1:10^{13} short-term stability
- Main Issue: How to get dual-frequency operation without a grating



Calc. Gain vs. Cavity Length for 0.5-m Laser

{Shown are only 626 I P18 and 628 I P25 transitions and those I P branch (10.6 µm) lines with higher gain}



At length ~ 100 µm shorter than LCDR, the 626 I P18 and 628 I P25 lines are well separated from other strong 10.6-µm lines

Criteria for Dual-Frequency Two-Mirror Mixed-Isotope CO_2 Laser

- **Short cavity (<0.5 m, 300 MHz FSR) to allow ~10 lines**
- **Low pressure (<20 torr, <50 MHz FWHM) allows ~ 10 lines**
- **$^{16}O/^{18}O$ isotope ratio optimized to balance gains**

The above leads to LOW GAIN

- **High-reflectivity mirrors (>99% spherical and >98% output)**
- **Selective coated surface in cavity to reject 9.5-µm lines**
- **Precise cavity length for line-center double resonance**
  - **(e.g. 487.356 mm for 626 I P18 / 628 I P25 beat at 2.15 GHz)**

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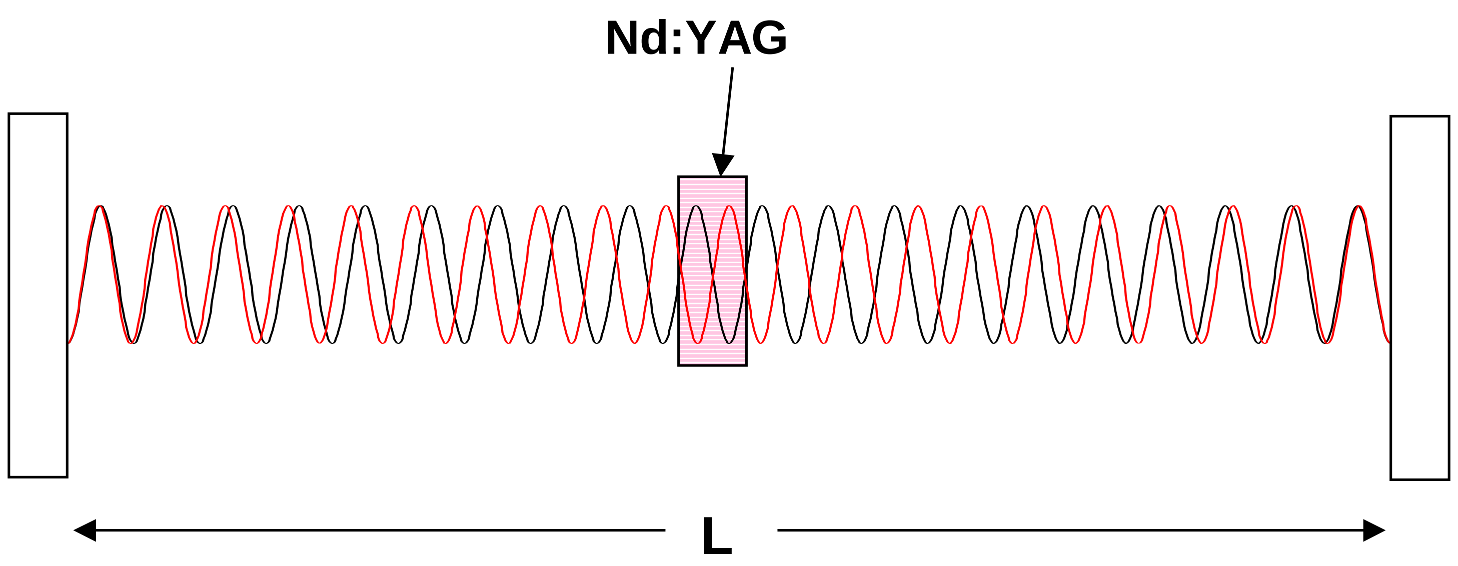
- ➔ Nd:YAG laser RF source
- Summary of proposed work

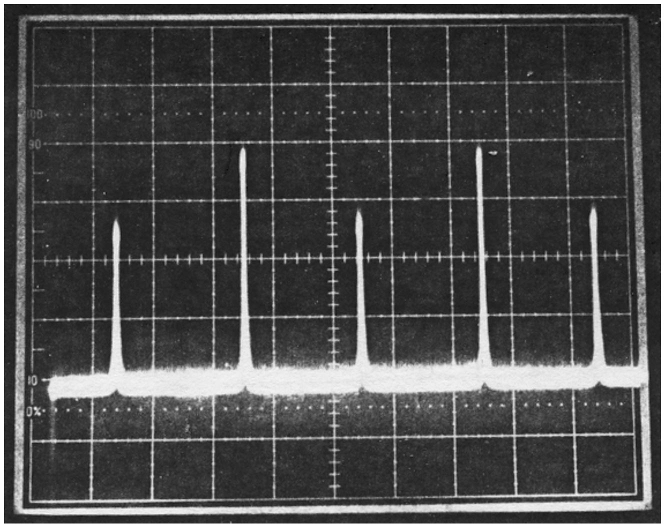
Standing-wave cavity lasing in two modes

- Spatial hole-burning causes the laser cavity to oscillate in exactly two longitudinal modes.
- The beat frequency will be equal to the cavity free-spectral-range (= c/2L).

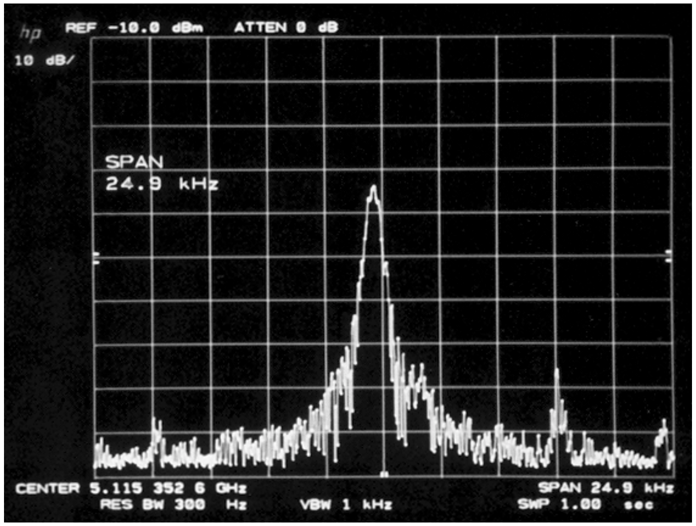


Two-mode Nd:YAG laser proof-of-principle experiment (1993)

- **Two-mode lasing has been demonstrated using the spatial-hole-burning technique.**
- **The initial demonstration was a table-top design, not intended to have excellent noise performance.**



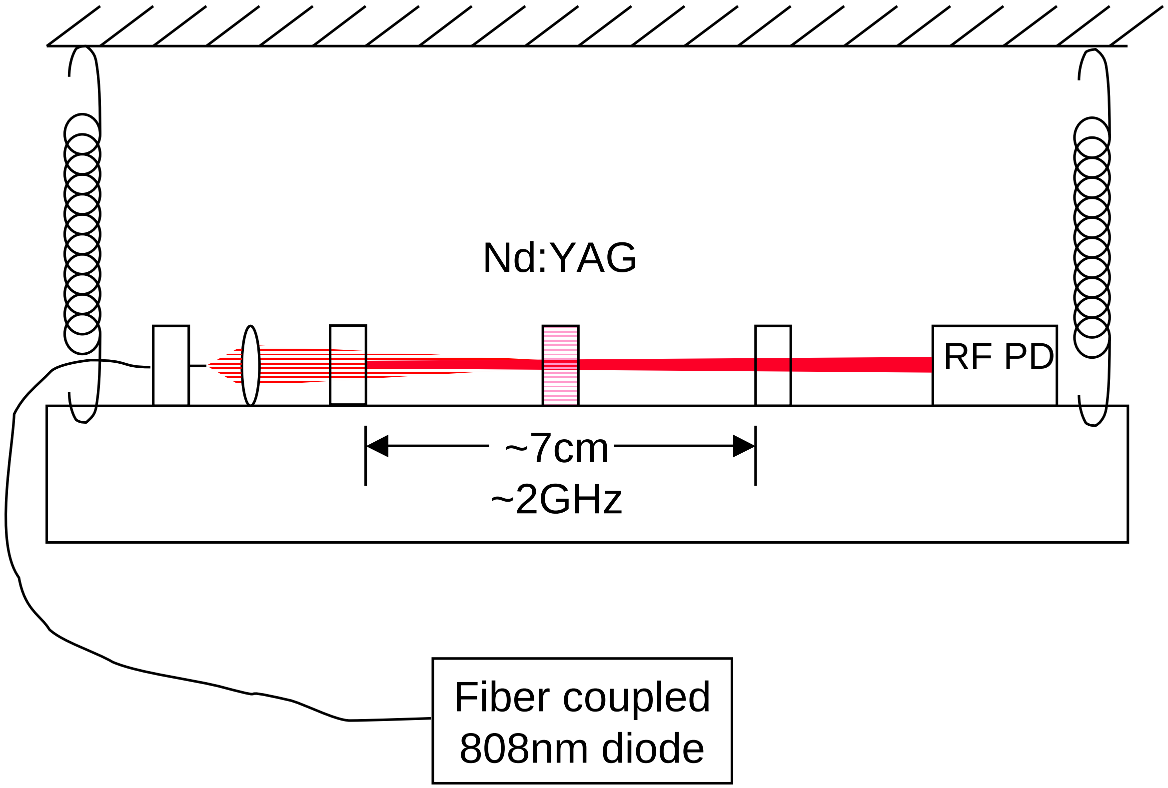
Scanning optical spectrum analyzer showing two modes



Spectrum analyzer trace of the RF beat frequency ~500 Hz linewidth at 5GHz

Proposed two-mode laser

- **Laser cavity, pump source, and RF photodiode are all mounted on a single block and seismically isolated inside a vacuum chamber.**



Proposed Work

- **Year 1 milestones**
  - **Contruct CO_2 and Nd:YAG two-frequency lasers**
  - **Identify technical noise sources (and eliminate if possible)**
  - **Measure Allan variance of laser RF sources**
  - **Optimize laser operation for minimum Allan variance**
- **Year 2 milestones**
  - **Construct second set of laser sources with upgrades**
  - **Measure absolute phase noise spectra**
  - **Continued optimization and identification of noise sources**